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GEOMETRY DEPENDENT BEAM DYNAMICS OF A 3.5-CELL SRF GUN CAVITY AT ELBE *

K. Zhou, Institute of Applied Electronics, CAEP, 621900 Mianyang, China
Institute of Radiation Physics, HZDR, 01328 Dresden, Germany
A. Arnold, J. Schaber, J. Teichert†, R. Xiang, S. Ma
Institute of Radiation Physics, HZDR, 01328 Dresden, Germany

Abstract

In order to optimize the next generation SRF gun at HZDR ELBE radiation source, the impact on beam dynamics from the SRF cavity geometry needs to be investigated. This paper presents an analysis on the electromagnetic fields and output electron beam qualities, by changing the geometry parameters of a 3.5-cell SRF gun cavity. The simulation results show the higher electric field ratio in the first half cell to the TESLA like cell, the better beam parameters we can obtain, which, however, will also lead to a higher Emax/E0 and Bmax/E0.

INTRODUCTION

Superconducting radio-frequency electron photo injector (SRF gun) can provide high-brightness and low-emittance electron beams in continuous wave (CW) mode with magahertz pulse repetition rates, which could be widely used for many accelerator facilities, such as free electron laser (FEL), energy recovery linacs (ERLs) and electron linear colliders. The concept of SRF gun was firstly proposed by Chaloupka and co-workers in 1988 [1], and the first experiments were carried out at the University of Wuppertal four years later [2]. In 2002, world's first electron beams were delivered by the Drossel SRF gun at FZR (now HZDR) [3]. Then, a superconducting photo injector (SRF GUN I) was developed for a linac at ELBE radiation source and successfully operated from 2007 to 2014 [4]. After that, an improved SRF gun (SRF GUN II) replaced the previous one and has been in operation up to now [5] (See Fig. 1).

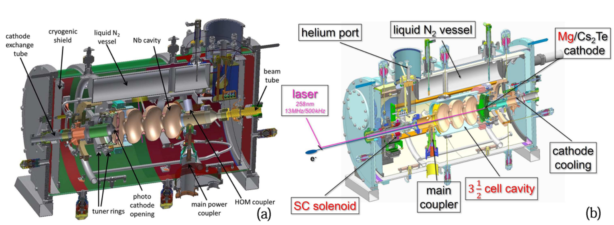

Figure 1: SRF GUN I (a) and SRF GUN II (b).

In order to achieve the goal of high average current (1mA) and low emittance (1 mm mrad @ 77 pC), some modificaitions has been applied on SRF GUN II, comparing to SRF GUN I. The field in the half cell is increased from about 60% to 80% compared to the field strength in one of the three TESLA like cells. Another significant change is the integration of a superconducting solenoid in the cryomodule, which makes it more compact and the distance to the cathode smaller [6]. The effects of emittance compensation including RF focusing, cathode position as well as superconducting solenoid have been analyzed [7].

Now, the next generation SRF gun is planning to be developed at HZDR ELBE radiation source. So, the impact on beam dynamics from the SRF cavity geometry needs to be considered. This paper presents an analysis on the electromaganetic fields and output beam qualities of several cavity models with different geometries.

CATITY MODELS

For a singe half cell, there are six parameters to determine its structure. They are length, R_{iris}, $R_{equator}$, R_c, a and b as shown in Fig. 2. The contour of a half cell consists of an elliptical arc, a circular arc and a straight line tangent to these two arcs.

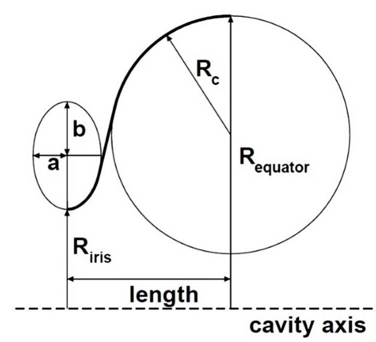

Figure 2: Contour of a half cell [8].

Figure 3 shows the contour of a 3.5 cell SRF cavity with a photocathode inserted into the cavity, which is composed of about 30 different geometry parameters. In the case of Fig. 3, the 3.5 cell cavity consists of a special designed half cell (Z0, Z1, R1, R2, a1, b1, r0 and r1) connected with the photo cathode and three TESLA like cells. The geometry values of the middle four half cells in the three TESLA like cells are all the same (Z3, R3, R5, a3, b3 and r3), while the front half cell (Z2, R2, R5, a2, b2, r2) and the end half cell (Z4, R4, R5, a4, b4 and r4) are a little different from the middle cells.

Table 1 lists the geometry values of the initial model: model_0, which is based on the geometry of SRF GUN I. The total length of the cavity is about 477 mm. When

* Work supported by National Natural Science Foundation of China with Grant [11605190 and 11805192].
† email address: j.teichert@hzdr.de

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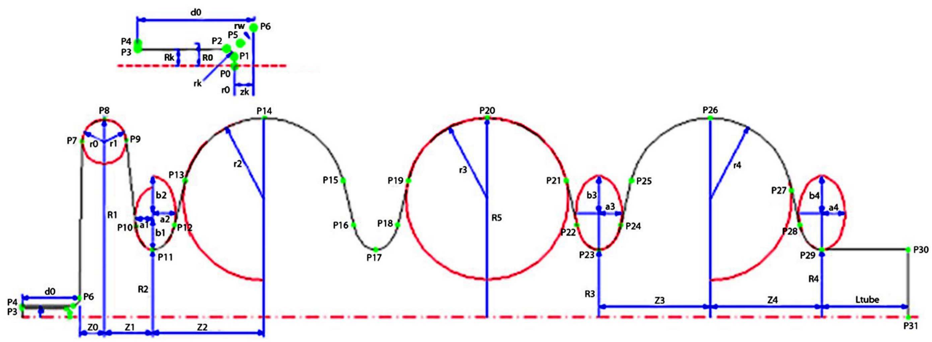

Figure 3: Geometry parameters of a 3.5-cell SRF gun cavity [9].

Table 1: Geometry Values of Model_0 (unit:mm)

Z0	Z1	R1	R2	a1	b1	r0	r1	d0	R0
12.65	25	102.58	35	9	9	11.40	11.40	30	6
Z2	a2	b2	r2	Z3	R3	R5	a3	b3	r3
51.89	12	19	37.01	57.65	35	103.3	12	19	42.86
Z4	R4	a4	b4	r4	LTube	Rk	zk	rk	rw
57	39	9	12.8	43.06	100	5	2.5	0.5	0.5

changing the geometry of the cavity, it should be noted that the resonant frequency should be kept almost unchanged and the field flatness should also be good enough. Since the kinetic energy of electrons in the half cell and first TESLA like cell is pretty low, the RF field there has much more influence on beam qualities than latter sections. So, this study mainly focuses on the area of the half cell and the first TESLA like cell as shown in Fig. 4.

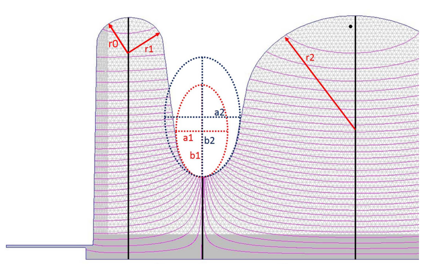

Figure 4: The changing areas of the cavity models.

Table 2 lists seven different cavity models from model-2 to model+4. By increasing (decreasing) Z1, a1 and b1 and decreasing (increasing) Z2, a2, b2, we can keep the total length of the cavity unchanged and the connecting point smooth. To compensate the frequency shift, r0&r1 and r2 need to be adjusted a little correspondingly.

Figure 5 shows the absolute electric fields on axis of these models normalized to Epeak = 50 MV/m, where Epeak refers to the maximum value of electric field along the central axis. The major differences of thier RF fields are located in the half cell. The physical parameters of these seven models caculated with Superfish are listed in Table 3, in which E0

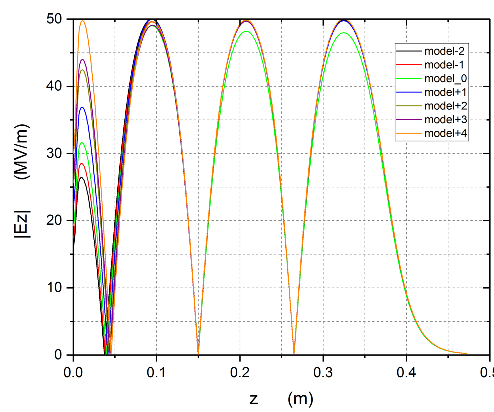

Figure 5: On-axis field profiles of these cavity models normalized to Epeak = 50 MV/m.

is the average electric field gradient along the central axis; Epeak1 is the maximum electric field gradient in the first half cell; Emax is the maximum electric field of the whole cavity and Bmax is the maximum magnetic field of the whole cavity. The resonant frequency and field flatness almost remain unchanged. The maximum shift of their frequencies is less than 75 kHz. Their field flatnesses are all better than 97%. The value of r/Q decreases a little but not much. The ratio of Epeak1 to Epeak increases from about 50% to 100% from model-2 to model+4. Meanwhile, both Emax/E0 and Bmax/E0 also increase significantly (about 55% and 43%, respectively).

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Table 2: Seven Cavity Models with Different Changes of the Half Cell and First TESLA like Cell (unit:mm)

models	Z1	a1	b1	r0&r1	Z2	a2	b2	r2
model-2	-2	-2	-1.5	0	+2	+2	+2	+0.4
model-1	-1	-1	-1	0	+1	+1	+1	+0.2
model_0	0	0	0	0	0	0	0	0
model+1	+1	+1	+1	0	-1	-1	-1	0
model+2	+2	+2	+2	0	-2	-2	-2.5	0
model+3	+3	+3	+3	+0.1	-3	-3	-3	-0.1
model+4	+4	+4	+4	+0.15	-4	-4	-4	-0.1

Table 3: Physical Parameters of These Seven Models Calculated with Superfish

models	Freq. (MeV)	E_0 (MV/m)	E_{peak1} (MV/m)	E_{peak} (MV/m)	E_{peak1}/E_{peak}	E_{max}/E_0	B_{max}/E_0 mT/(MV/m)	Field Flatness	r/Q
model-2	1297.631	10	9.59	18.1	52.9%	2.052	4.142	99.4%	340.5
model-1	1297.61	10	10.3	18.1	57.0%	2.024	4.112	99.2%	339.4
model_0	1297.677	10	11.7	18.2	64.5%	2.174	4.285	97.8%	336.8
model+1	1297.646	10	13.1	17.8	73.8%	2.431	4.713	99.5%	333.6
model+2	1297.624	10	15.0	17.6	84.9%	2.755	5.254	99.2%	328.7
model+3	1297.605	10	15.5	17.6	88.0%	2.856	5.396	98.2%	327.1
model+4	1297.632	10	17.3	17.3	99.6%	3.170	5.916	99.2%	321.5

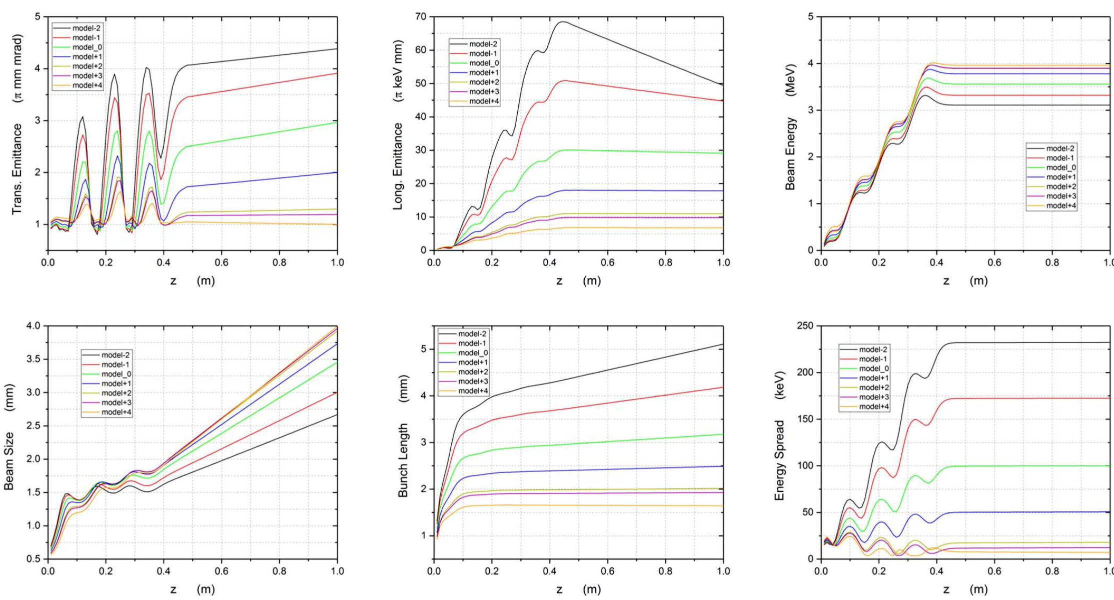

Figure 6: Output beam parameters when Qbunch = 100 pC, Epeak = 20 MV/m, Laser phase = 50 deg.

SIMULATION RESULTS

In previous cavity geometry optimizations, the physical parameters of the RF field are always the main optimized goals, while in this paper, the impact of the beam dynamics from the RF field will be taken into account. We extract the RF field from Superfish output files and caculate the output beam parameters with Astra. In order to compare the influences of the cavity geometry separately, the simulation does not consider the bias voltage applied on the photocathode and the solenoid located at the downsteam of the SRF cavity. The initial electron distributions at the photocathode are all the same for different models. The bunch charge is 100 pC. The laser pulse length is 3 ps and the initial rms radius is 0.5 mm.

Figure 6 shows the simulation results when Epeak=20 MV/m and laser phase = 50 deg. The laser phase means the relative phase between the laser pulse and the RF field, which is also the initial RF phase that the electrons see at the photocathode.

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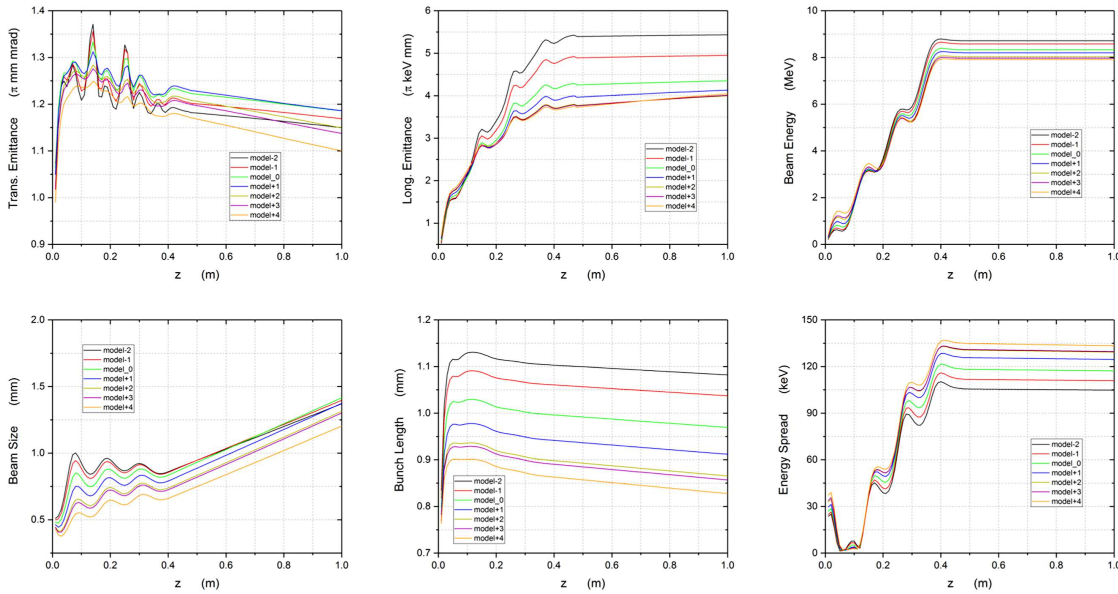

Figure 7: Output beam parameters when Qbunch = 100 pC, Epeak = 50 MV/m, Laser phase = 50 deg.

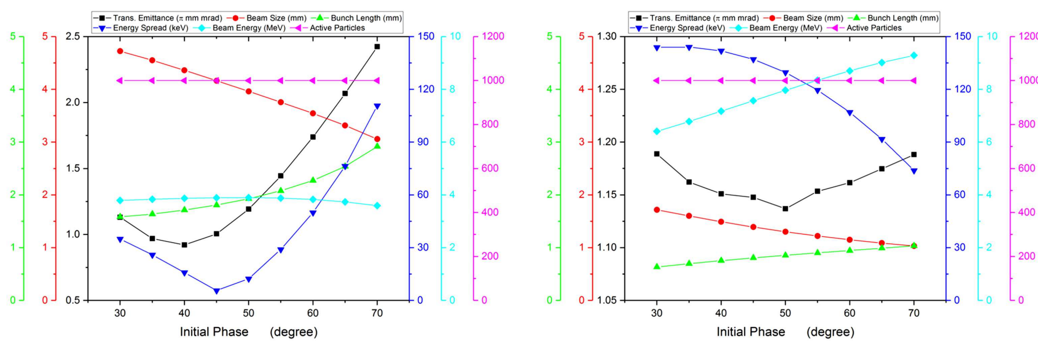

Figure 8: Phase scan of model+3 when Epeak = 20 MV/m (a) and Epeak = 50 MV/m.

In Fig. 6, there are six beam parameters versus the longitudinal axis z being compared. They are transverse emittance, beam size, longitudinal emittance, bunch length, beam energy and energy spread. The length of axis z starts from the surface of the photocathode and ends at 1 m. The total length of the SRF cavity is about 477 mm and the rest is free space drift. The field gradient and RF phase are near our current operating state of SRF GUN II, when Epeak = 20 MV/m and laser phase = 50 deg. From the simulation results, all the parametres except beam size are becoming significantly better when the cavity model changing from model-2 to model+4, while the increasing of beam size can be compensated with solenoid or quadrapoles easily. Especially, the transverse emittance can be reduced from 4 mm mrad to 1 mm mrad. That is to say, with the increasing of the field gradient ratio in the half cell to the TESLA like cell, the output beam parameters can be improved markedly when operating at Epeak = 20 MV/m.

We also investigate the situation when the field gradient of Epeak increasing to 50 MV/m, which is the designed value of SRF GUN II, as shown in Fig. 7. In the case of 50 MV/m, the effective field gradient is much higher and the emittance, beam size and bunch length are much smaller than the ones in the case of 20 MV/m. For these cavity models, their transverse emittances do not have much differences, varying betwenn 1.1 mm mrad and 1.2 mm mrad. But the longitudinal emittance and the bunch length are still decreasing from model-2 to model+4, as well as the beam size. It should be noted that the variation trends of beam energy and energy spread are contrary in Fig. 6 and Fig. 7, which means that it needs to sacrifice a little acceleration efficiency to obtain better other beam parameters with the increase of Epeak.

Above all, model+2, model+3 and model+4 provide better output beam parameters than model-2, model-1 and model_0 at both Epeak = 20 MV/m and Epeak = 50 MV/m. Finally, we scan the laser phase of model+3 at Epeak = 20 MV/m and 50 MV/m and observe the output beam parameters at 1 m

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as shown in Fig. 8. At 20 MV/m, the phase corresponding to the minimum transverse emittance and ernergy spread are 40 deg and 45 deg, which is in accordance with our experiments. At 50 MV/m, the phase correspoding to the minimum transverse emittance shifts to 50 deg.

CONCLUSION

By changing the geometry parameters around the half cell and first TESLA like cell, we obtained seven different cavity models with the ratio of Epeak1 to Epeak varying from about 50% to 100%. The simulation results indicate the higher electric field ratio in the half cell to the TESLA like cell, the better beam parameters we can get. However, it will also lead to relatively higher Emax/E0 and Bmax/E0, which would increase the risk of field emission and thermal breakdown.

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